

AD-A122 851

THEORY OF HIGH SPEED DISPLACEMENT SHIPS WITH TRANSON  
STERNS(U) HYDRONAUTICS INC LAUREL MD M P TULIN ET AL.  
SEP 82 TR-8035-1 N00014-80-C-0669

1/1

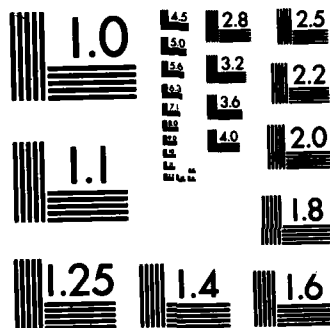
UNCLASSIFIED

F/G 13/10. NL

END

FORMED

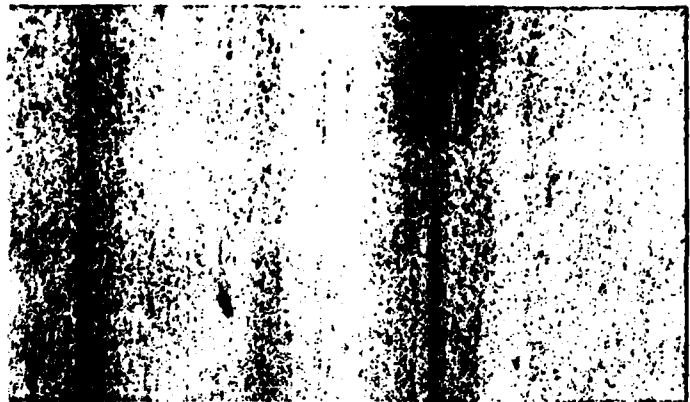
DATE



MICROCOPY RESOLUTION TEST CHART  
NATIONAL BUREAU OF STANDARDS-1963-A

12

AD A122851



S  
JAN 0 3 1983  
E

FILE COPY

# HYDRONAUTICS, incorporated research in hydrodynamics

Research, consulting, and advanced engineering in the fields of NAVAL and INDUSTRIAL HYDRODYNAMICS. Offices and Laboratory in the Washington, D. C., area: Pindell School Road, Howard County, Laurel Md.

12

HYDRONAUTICS, Incorporated

TECHNICAL REPORT  
8035-1

THEORY OF HIGH SPEED DISPLACEMENT  
SHIPS WITH TRANSOM STERNS

by

Marshall P. Tulin\*  
C. C. Hsu

September, 1982

Prepared for  
Office of Naval Research  
Under  
Contract No. N00014-80-C-0669  
NR 062-596

\* Present Address; Dept. of Mechanical and Environmental Engineering  
University of California, Santa Barbara, CA 93106

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER TECHNICAL REPORT 8035-1	2. GOVT ACCESSION NO. AD A122 851	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) THEORY OF HIGH SPEED DISPLACEMENT SHIPS WITH TRANSOM STERNS		5. TYPE OF REPORT & PERIOD COVERED Technical Report September 1982
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Marshall P. Tulin C. C. Hsu		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS HYDRONAUTICS, Incorporated 7210 Pindell School Road Laurel, Maryland 20707		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Department of the Navy Office of Naval Research		12. REPORT DATE September 1982
		13. NUMBER OF PAGES 36
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) <div style="border: 1px solid black; padding: 5px; text-align: center;">This document has been approved for public release and sale; its distribution is unlimited.</div>		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)  DISTRIBUTION UNLIMITED		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Displacement Ships Transom Sterns High Speeds Shadow Regions Wakes Stern Induced Resistances		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A theory has been developed for high speed displacement ships. The theoretical treatment is based on treating the hull as finite in beam and draft but slender and the flow at the aft waterline being smooth and with a trailing wake. The trailing wake results in substantial residuary resistance at high speed for normal waterline shapes. Calculations are made for ships of highly variable parametric form and the results given. It seems that		

DD FORM 1473  
1 JAN 73EDITION OF 1 NOV 68 IS OBSOLETE  
S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. the resistance, at high speed, may be greatly reduced through proper after-body design. A comparison of calculated results with the experimental results of NSRDC Series 64 shows good agreement and lends credence to the theory.

HYDRONAUTICS, Incorporated

-i-

TABLE OF CONTENTS

	<u>Page No.</u>
INTRODUCTION . . . . .	1
THEORY . . . . .	4
SOLUTION . . . . .	8
RESULTS . . . . .	12
EXTENSIONS . . . . .	16
SUMMARY AND CONCLUSIONS . . . . .	17

Accession For	
NTIS GRA&I	<input checked="checked" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A	



RE: Distribution Statement  
Unlimited per Dr. Robt. E. Whitehead,  
ONR/Code 432

### INTRODUCTION

There is considerable interest in high speed displacement ships. These are characterized by high length-beam ratios, sharp bows, and flat sterns terminating in a transom. Such ships have been constructed for naval purposes, for example the German WWII Jaguar boats and their derivative the current Israeli missile boats, originally French built. All of these ships are reported to combine high surface speed with excellent seakeeping characteristics.

Systematic tests of conventional high speed forms were carried out at the David Taylor Model Basin and reported by H.Y.H. Yeh in 1964, Reference 1. These tests, comprising a series of 27 models, involved systematic variation in beam-draft ( $B/H = 2, 3, 4$ ) and block coefficient ( $C_B = 0.35, 0.45, 0.55$ ); the resulting length-beam ratios varied from about 8.5 to 18.0; the transoms were in general very full, their width being not too much smaller than the maximum beam.

The test results show a very significant residuary coefficient at the highest speed-length ratios, often exceeding 50 percent of the residuary pertaining at a speed length ratio ( $V/\sqrt{L}$ ) of 1.5, where wave resistance may be expected to be a maximum, see Figures 1A and 1B.

These results, taken together with the very fact of the wide transom stern evolution in design, raises some extraordinarily interesting questions concerning the hydrodynamics of these ships:

1) Since wave resistance is generally believed to decrease rapidly at high  $V/\sqrt{L}$  toward a value of zero, what exactly is the nature of the very large measured residuaries at high  $V/\sqrt{L}$ ? Spray? Other??



2) Why are open sterns (transoms) desirable at high speeds?

After all, for submerged slender bodies, there is generally a positive form drag associated with open sterns.

Planing vessels have been rather extensively treated and rather good methods based on theory exist for the prediction of their performance, References 2 and 3; and the nature of their resistance (spray and "induced") is fairly well understood for slender surfaces, Reference 4. Strangely enough, however, there does not seem to exist any theory pertaining to the flow about high speed displacement ships, aside from preliminary theoretical considerations, such as those of Ogilvie, Reference 5. Nor is there a theory of transoms, except for the numerical calculations of Van Eseltine and Haussling, Reference 6. We certainly have not found answers to the two most interesting and important questions 1) and 2) above. Pertinent theory might not only answer these questions but provide methods for optimizing design, especially of the transom.

In view of this situation, the senior author initiated a theoretical study of slender high speed displacement ships under ONR Contract N00014-80-C-0669, with the results described below.

The theory is asymptotic to  $V/\sqrt{L} = \infty$  (no gravity), and assumes  $B/H = O(2)$  and  $B/L \ll 1.0$ . All of these conditions seem realized in the high speed tests of Reference 1.

Most important, it is pointed out at the outset that the solution to the problem is not unique and that the physically realizeable solution involves in general, a "wake" flow behind the ship which carries energy and therefore results in resistance. This resistance is in general reduced by widening a suitable transom, and may in fact be annulled by a suitable transom with a width at the waterline equal to the ship's maximum beam.

The theory is given analytical form and reduced finally to a boundary value problem in the cross flow plane, which must be solved for each cross section of the ship. A computer program is utilized to solve this problem and rather extensive calculations of resistance made for ships comprising Series 64, Reference 1. The results are excellent at the highest values of  $B/H$  and not bad for other values.

The results seem important; they suggest: a) that the greatest part of resistance of high speed displacement ships is due to the stern (we call it "stern-induced" resistance) and not to spray! b) that the "stern-induced" resistance may be eliminated through proper after-body design, and that the very existence of transoms lies in their ability to reduce such resistance; c) that the usual wave resistance problem is not completely posed, that the solution is not unique, and that the solution normally taken in existing theory, at least at high speeds, may result in physically unrealizable solutions.

Finally we point out that the theory may be applied to ships with yaw, and suggest that a sideforce linear in yaw results at high speed and can be calculated.

Directions for extension of the theory are pointed out.

THEORY

We are concerned here with slender ships ( $B/H = O(2)$ ;  $B/L \ll 1$ ) operating at "high" speeds ( $U_0^2/gL \gg 1$ ). We assume that the effects of viscosity are secondary. Consequently:

1) On the free surface, where  $p = \text{constant}$ , the speed  $q$  is everywhere the same and equal to the approach velocity,  $U_0$  far ahead of the ship. ( $q = \sqrt{U^2 + v^2 + w^2}$  where  $U = U_0 + u$ ,  $v$  and  $w$  are the  $(x, y, z)$  components of velocity, and where  $u, v, w = \phi_{x, y, z}$ ).

2)  $\nabla^2 \phi = 0$  everywhere and  $\nabla^2 \phi \approx \phi_{yy} + \phi_{zz} = 0$ ; therefore  $\phi = R[\Psi(x; z + iy)]$ .  $q \approx U_0 + \phi_x$ .

3) The free surface may be taken in the  $(x-z)$  plane (i.e. at  $y \equiv 0$ ).

4) On the free surface,  $y = 0$ :  $\phi_x = 0$ , or  $\phi(x, 0, z) = \phi(z)$ .

5) The free surface consists of four separate regions, see Figure 2, a plan view. The entire free surface is  $S$  and the intersection of  $S$  and the hull is  $N$ , which defines the waterline shape. In  $S_0$ , the region outside the maximum beam:  $\phi = 0$ , since  $\phi(-\infty, 0, z) \equiv 0$ . In  $S_1$ , the forward shadow of the ship:  $\phi = 0$ , except in a narrow boundary near  $N$  which is the spray region  $S_s$ . In the narrow boundary layer  $S_s$  the flow on  $S_1$  (where  $w = 0$ ) adjusts itself very rapidly to the condition on  $N$  where

$$w \approx \pm \frac{U_0}{2} \frac{db}{dx} ;$$

( $b(x)$  is the local beam of the waterplane). Physically, this adjustment is experienced as a thin spray sheet. In  $S_2$ , the rear shadow of the ship there are two distinct possibilities:

- i)  $\phi = 0$
- ii)  $\phi_z(x, z) = \phi_z(x_N; z)$ , where  $\phi_z(x_N; z) \approx U_0 \frac{dz_N}{dx} = \pm \frac{1}{2} U_0 \frac{db}{dx}$  [1]

The former possibility (i) would again require a narrow boundary layer along  $N$  wherein the lateral flow would adjust itself from its value on the hull to the value  $w = 0$  in the shadow. But the resulting solution requires (in this approximation) that flow detach from the hull with infinite vertical velocity and move downward to reach the water level downstream. In Figure 3 the free surface shape is shown schematically for a section of the bow and of the stern, according to both i) and ii) above. The "inverted spray" solution indicated by i) would lead to a narrow but high sheet of water between the hull and the wake surface everywhere along the stern and is not observed in practice, while the "smooth" flow indicated by ii) seems typical of observation. We therefore choose ii). This choice is equivalent to imposing the Kutta condition at the trailing edge of a slender wing or planing surface of waterline shape  $N$ .

6) As a result of ii), there exists in the entire rear shadow of the hull, prescribed values of  $w$  on the free water surface in  $S_2$ , see Figure 4.

7) On the hull surface:

$$\nabla (U_0 x + \phi) \cdot \vec{n} = 0 \quad [2]$$

where  $\vec{n}$  is the outer normal (vector) at any point on the hull,

and is given by:

$$\vec{n} = (n_x; n_y; n_z) = (\sin\beta; -\cos\beta \cos\alpha; \cos\beta \sin\alpha)$$

where  $\beta$  is the angle between the vector  $n_z + i n_y$  and  $n$ , and is given by (the subscript M refers to points on the hull):

$$\tan\beta = \cos\alpha \cdot \frac{\partial y_M}{\partial x}$$

or,

$$n_x = - \left[ n_y \frac{\partial y_M}{\partial x} - n_z \frac{\partial z_M}{\partial x} \right] \quad [3]$$

Finally, assuming  $\phi_x/U_0 \ll 1$ , Equation [2] yields:

$$\phi_y|_M = U_0 \frac{\partial y_M}{\partial x}; \quad \phi_z|_M = U_0 \frac{\partial z_M}{\partial x} \quad [4]$$

or, assuming in addition that  $\cos\beta \approx 1$ :

$$\phi_n = U_0 \left[ \cos\alpha \frac{\partial y_M}{\partial x} - \sin\alpha \frac{\partial z_M}{\partial x} \right] \quad [5]$$

8) Finally, in view of 1-7 above, the problem is reduced to a set of two dimensional potential problems in the cross flow plane as shown in Figure 5. Notice that the problem may be replaced by another which is equivalent, in which the hull beneath the water surface is augmented by its reciprocal above the surface, such that the equivalent body is source free in the far field, and may be represented by a dipole distribution; the flow is thus essentially wing-like. In this representation the surface  $S_2$  comprises a trailing vortex wake, and condition ii) of paragraph 5 is mathematically equivalent to the imposition

of the trailing edge Kutta condition in the case of a slender wing, as noted earlier. The representation of the hull and its reciprocal involves additional vorticity. At the transom, the hull (plus reciprocal vorticity) plus free surface wake is shed into the ship's wake (plus its reciprocal) and manifests both the lift acting on the hull (vertical momentum in the wake) and the stern-induced resistance of the hull (kinetic energy in the cross flow).

9) The narrow spray region  $S_2$  corresponds to the leading edge region on a slender flat wing. In the latter case, the inability of the flow to follow the wing (go around the leading edge) leads to loss of leading edge suction and therefore to a resistance which is non-zero in the case of separation at the leading edge. The non-zero value of leading edge suction follows from the nature of the singularity at the leading edge of the flat wing

$$(\psi' = w - iv \sim \frac{1}{\sqrt{\zeta}}, \text{ where } \zeta = z + iy) .$$

In the case of a displacement ship with a vertical side at N, then it can be shown that  $\psi' \sim \ln \zeta$  and that the waterline suction and therefore the spray resistance is zero in the present approximation. This surprising conclusion would seem to be borne out by our later comparison of predicted stern-induced resistance with experiments.

SOLUTION

The flow about the ship, according to 2) above, can be described by a complex potential,

$$\Psi = \Psi(x; y, z) = \phi + i\psi$$

where  $\Psi$  is an analytical function of  $\zeta = z + iy$ . The complex velocity is:

$$\frac{d\Psi}{d\zeta} = \Psi'(x; y, z) = w - iv$$

and the velocity field is given by,

$$\nabla(U_0 x + \phi) = [U_0 + \phi_x; \phi_y; \phi_z] = [U_0 + \phi_x; -I(\Psi')'; R(\Psi')] \quad .$$

The complex velocity at each value of  $x$  may be represented in terms of a distribution of a suitable Green's function:

$$\Psi'(x; \zeta) = \int \frac{Q(x; \zeta_1)}{2\pi} G(\zeta, \zeta_1) d\zeta_1$$

$$M(x) + M^*(x) \quad [6]$$

where  $Q(x; \zeta_1)$  represents the strength of the singularity distribution due to the presence of the ship equivalent boundary,  $M + M^*$ . A suitable Green's function in the present problem is the source:

$$G(\zeta, \zeta_1) = \frac{1}{\zeta - \zeta_1}$$

so that  $Q$  is the complex source strength.

The contour  $M$  includes the submerged hull  $M_\ell$  and its reciprocal  $M_u$ , and  $M^*$  includes the vortex sheet on the free surface  $S_2$ , Figure 5, where  $\zeta_u = \bar{\zeta}_\ell$ , the overbar indicating the complex conjugate.

If  $Q_\ell$  is the source strength on  $M_\ell$ , and  $Q_u$  on  $M_u$ , then  $Q_u = \bar{Q}_\ell$  satisfies the boundary condition on  $S_0$  ( $w=0$ ). Equation [6] may thus be written:

$$\Psi'(x; \zeta) = \frac{1}{2\pi} \int_{M_\ell} \left\{ \frac{Q d\zeta_1}{(\zeta - \zeta_1)} - \frac{\bar{Q} d\bar{\zeta}_1}{(\zeta - \bar{\zeta}_1)} \right\} + \frac{i}{2\pi} \int_{M^*} \frac{\gamma dz_1}{(\zeta - z_1)} \quad [7]$$

Since the integral on  $M_\ell$  contributes not at all to  $w$  on  $M^*$ , then on  $S_2$ :

$$\gamma(z_1) = -2w(z_1), \text{ the latter being prescribed by [1].}$$

Now, it is possible to show that,

$$-ie^{i\alpha} \Psi' = \phi_n - i\phi_s \quad [8]$$

where  $s$  is the counterclockwise direction along the hull  $M_\ell$ .

Combining [7] and [8]:

$$R \left\{ -\frac{ie^{i\alpha}}{2\pi} \int_M \left\{ \frac{Q d\zeta_1}{(\zeta - \zeta_1)} - \frac{\bar{Q} d\bar{\zeta}_1}{(\zeta - \bar{\zeta}_1)} \right\} - \frac{e^{i\alpha}}{\pi} \int_{M^*} \frac{w(x; z_1) dz_1}{(\zeta - z_1)} \right\} = \phi_n(\zeta) \quad [9]$$

for all  $\zeta$  on  $M_\ell$ . Since  $\phi_n(\zeta)$  is known in terms of the hull shape, see Equation [5], this represents an integral equation for  $Q(x; \zeta)$ .



The effects of the body 'shape and stern wake on S may be decoupled by seeking:

$$Q = m + i \gamma$$

where

$$R \left\{ - \frac{ie^{i\alpha}}{2\pi} \int_{M_\ell} \left\{ \frac{md\zeta_1}{(\zeta - \zeta_1)} - \frac{md\bar{\zeta}_1}{(\zeta - \bar{\zeta}_1)} \right\} \right\} = \phi_n(\zeta) \quad [10]$$

for all  $\zeta$  on  $M_\ell$ .

$$R \left\{ \int_{M_\ell} \left\{ \frac{\gamma d\zeta_1}{(\zeta - \zeta_1)} + \frac{\gamma d\bar{\zeta}_1}{(\zeta - \bar{\zeta}_1)} \right\} - 2 \int_{M^*} \frac{w(x; z_1) dz_1}{(\zeta - z_1)} \right\} = 0$$

so that the body boundary conditions in the absence of shed vorticity are satisfied entirely by the hull source distribution,  $m$ ; and the effect of the shed vorticity is represented by an additional induced vorticity distribution,  $\gamma$ . These integral equations, of the Neumann type, can be solved numerically for  $Q(\zeta)$  on  $M_\ell$ .

To the slender body approximation, Bernoulli's equation becomes:

$$p = -\frac{1}{2}\rho(u^2 + v^2 + w^2) - \rho U_0 \frac{\partial \phi}{\partial x} \approx -\rho U_0 \frac{\partial \phi}{\partial x} \quad [11]$$

The incremental lift ( $dL_f$ ) and resistance ( $dD$ ) may be determined from knowledge of the pressure acting on a transverse slice:

$$\frac{dL_f}{dx} = \int_{M_\ell} p \, dz \approx -\rho U_0 \int_{M_\ell} \frac{\partial \phi}{\partial x} \, dz \quad [12]$$

$$\frac{dD}{dx} = - \int p n_x dz \approx \rho U_o \int \frac{\partial \phi}{\partial x} \frac{\partial \phi}{\partial n} dz \quad [13]$$

The total lift and resistance may then be approximated by:

$$L_f = \int_0^L \frac{dL_f}{dx} dx \approx -\rho U_o \int_{M_\ell} \phi dz \Big|_0^L \quad [14]$$

$$D = \int_0^L \frac{dD}{dx} dx \approx \rho U_o \int_{M_\ell} \phi \frac{\partial \phi}{\partial n} dz \Big|_0^L \quad [15]$$

$$-\rho U_o \int_0^L \int_{M_\ell} \phi \frac{\partial}{\partial x} \left( \frac{\partial \phi}{\partial n} \right) dz dx$$

RESULTS

Extensive numerical studies have made for ships of the form:

$$y_m(x, z) = -h(x) \left[ 1 - (z/\frac{b}{2})^2 \right]^{n_1} \quad [16]$$

with

$$b = b_0 \left( \frac{x}{L} \right)^{n_2} \left( 1 - n_6 \frac{x}{L} \right)^{n_3}, \quad [17]$$

$$h = h_0 \left( \frac{x}{L} \right)^{n_4} \left( 1 - n_7 \frac{x}{L} \right)^{n_5} \quad [18]$$

The parameter  $n_1$  characterizes the fullness of the ships cross-section. Parameters  $n_2$ ,  $n_3$  and  $n_6$  govern the waterline profiles. Parameters  $n_4$ ,  $n_5$  and  $n_7$  determine the draft variations. Calculations of both the lift and resistance have been made. However, in the following only the resistance results, which are of particular interest, will be discussed in some detail. The parameters  $n_1$ ,  $n_2$ ... etc are varied from a parent ship of the form:

$$n_1 = 0.4, n_2 = 1.0, n_3 = 0.5, n_4 = 0.25$$

$$n_5 = 0.5, n_6 = 0.87, n_7 = 0.9$$

$$\frac{L}{B} = 10, \frac{B}{H} = 4.0$$

where B and H are the maximum beam and draft of the ship. In these Figures, the resistance has been nondimensionalized by  $\frac{1}{2}\rho U_0^2 B^2$  and given by

$$C_D = \frac{D}{\frac{1}{2}\rho U_0^2 B^2} = C_{D_1} + C_{D_2} \quad [19]$$

in which  $C_{D_1}$  and  $C_{D_2}$  represent the contributions by the source (hull alone) and the vorticity (trailing wake caused) distributions respectively. The resistances due to source distributions ( $C_{D_1}$ ) are generally small, so that the resistance calculated is largely "stern induced", accompanying the trailing wake from the aft waterline.

The dependence of  $C_D$  on ship cross section fullness is shown in Figure 6. The values of  $C_D$  are small for ships of very full cross section and increase with increase in  $n_1$  until it reaches a maximum and then decrease with further increase in  $n_1$ . The effects of the parameters  $n_2$  and  $n_3$  (which determine the fullness of the waterline profile) on  $C_D$  are given in Figures 7 and 8. The resistances are smaller for finer bows (larger  $n_2$ ) and fuller sterns (smaller  $n_3$ ). The values of  $C_D$  with various parameter  $n_4$  and  $n_5$  which largely determine the draft variations near the bow and stern respectively are shown in Figure 9 and 10 and are smaller for higher rake bows (smaller  $n_4$ ) and sharper keel-rise sterns (larger  $n_5$ ). Although the effect is small over most of the range. In Figure 11, the strong variations of  $C_D$  with parameter  $n_6$  which dictates the location of maximum beam is given. The resistance is smaller for the location of maximal beam nearer to the stern. The effect of  $n_7$ , which determine the draft near stern, on  $C_D$  is shown in Figure 12. The resistance is smaller for shallower sterns (larger  $n_7$ ). The dependence of  $C_D$  on length-beam and beam-draft ratios is shown in Figures 13 and 14. The resistances are seen to decrease with increasing in length-beam and beam-draft ratio.

The variations in resistances, except for parameters  $n_3$  and  $n_6$ , are moderate for various parameter changes. The resistances are very sensitive to the variations in  $n_3$  and  $n_6$  as can be seen in Figure 8 and Figure 11. The resistance can be reduced substantially if the maximum beam can be moved more toward the stern (by decreasing  $n_6$ ). If the changes in beam near the stern can be made more gradual (by decreasing  $n_3$ ), the resistance can also be drastically reduced. These results seem to indicate that superior ship resistance characteristics at high speed may be achieved by proper shaping the waterline profiles around the stern.

These results are consistent with the fact that a waterline with maximum beam at the transom and with zero slope there ( $db/dx = 0$ ) will not create a trailing wake and will therefore be free of resistance  $C_{D_2}$ . In fact  $\phi_n \equiv 0$  at every point on the transom then  $C_{D_1} = 0$  too.

Numerical calculations for ship forms very similar to those of Series 64 high-speed displacement forms, Reference 1 are also made. The values of various parameters for these computations are given below:

$$n_2 = 0.975, n_3 = 0.525, n_4 = 0.25, n_6 = 0.865$$

$$\left. \begin{array}{l} n_1 = 0.275, n_5 = 0.485, n_7 = 0.91 \\ n_1 = 0.65, n_5 = 0.525, n_7 = 0.954 \end{array} \right\} \text{for } C_B(\text{block coefficient}) = \left\{ \begin{array}{l} 0.55 \\ 0.45 \end{array} \right.$$

These series of displacement hulls have the same waterline profiles but have different draft variations for different block coefficients. Comparisons between the calculations and the experimental residual resistance data (non-dimensionalized by  $\frac{1}{2}\rho U_0^2 B^2$ ) measured at the speed length of five by Yeh (Reference

1) are shown in Figures 15a and 15b. The results are generally in good agreement, and especially for  $B/H = 3.0$  and  $4.0$ . Certainly the results would lend general confidence to both the theoretical developments and method of calculation.

EXTENSIONS

The theory presented here applies in the limit of very high speeds. A decrease in Froude number will involve both hydrostatic and wave sources of resistance. The hydrostatic effect on the transom is easily estimated. The waves must be the subject of additional theory, and an asymptotic theory (wavenumber small) suggests itself and could prove effective in the regime of high but finite speeds.

As noted in the introduction, a sideforce linear in yaw or sideslip develops due to the trailing wake and can be calculated.

The case of unsteady motions of the ship can be treated by the same kind of theory, possibly including motions in waves with forward speed (high speed limit).

And, finally, some of the startling results of the present paper deserve experimental verification. In that case, trim should also be calculated using the present results.

SUMMARY AND CONCLUSIONS

1) A theory has been developed and reduced to computation which applies to displacement ships in the limit of very high speeds.

2) Transom sterns may be treated.

3) The theoretical treatment is based on treating the hull as finite in beam and draft, but slender. It seems especially appropriate in the case of high speed ships which typically have large length/beam ratios.

4) In considering the consequences of the constant pressure condition on the free surface at high speeds it is revealed that two essentially different conditions can be imposed in the region aft of the maximum beam of the ship (in its shadow). One of these involves a thin sheet of water flowing rapidly down all along the aft waterline (inverted spray), and is discarded as physically unreal. The other involves a smooth flow at the aft waterline and a trailing wake (horizontal velocities on the free surface in the shadow). It seems physically realizable and corresponds to flows satisfying the Kutta condition at the trailing edge of slender wings.

5) Calculations are made for ships of a highly variable parametric form (seven constants) and the results given.

6) The trailing wake results in substantial residuary resistance at high speeds for normal waterline shapes. This is a completely new finding.

7) This residuary is typically reduced by widening the transom and is minimized by taking the maximum beam at the transom with sides there parallel to the flow direction. A shallow draft at the transom is also indicated.

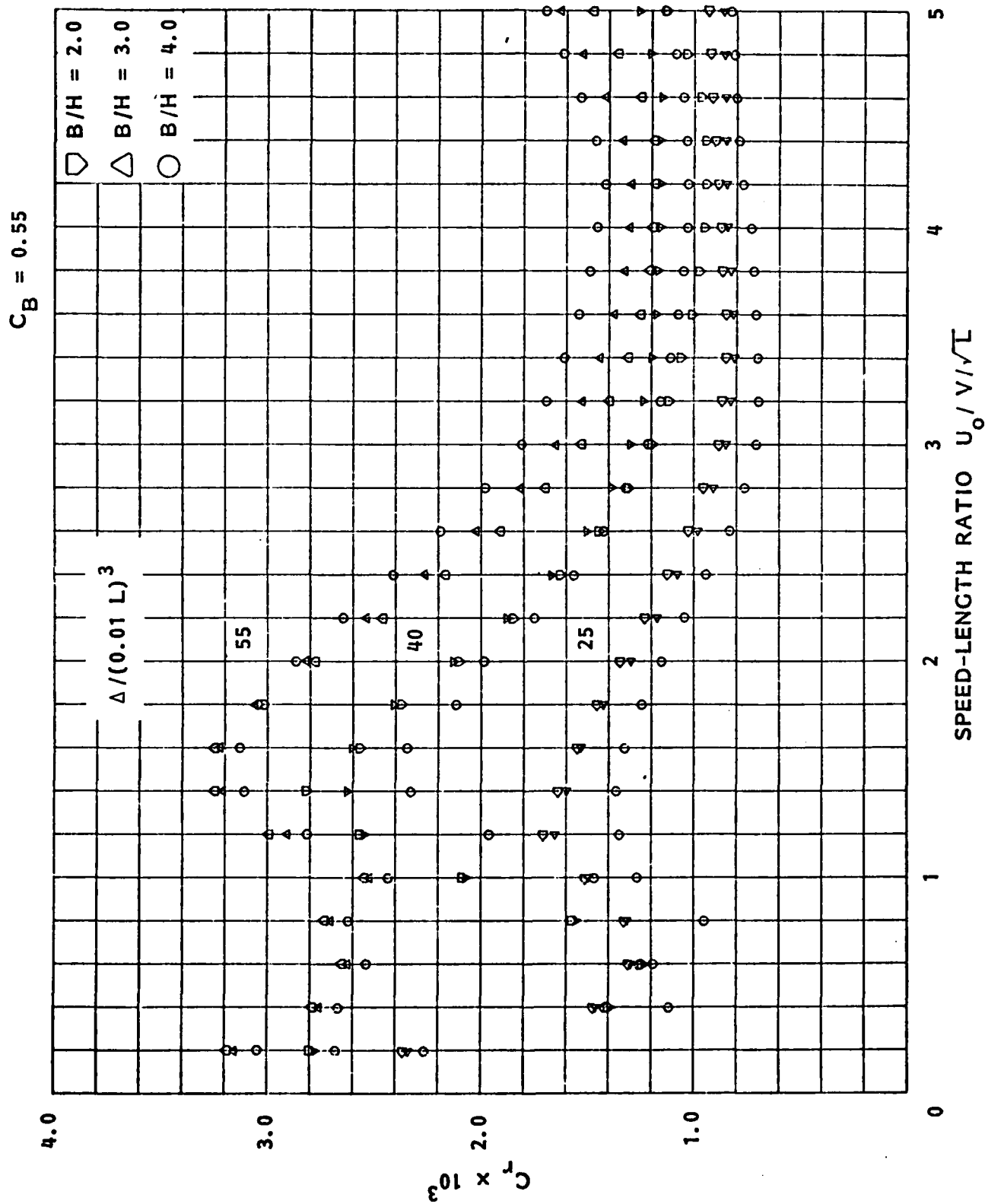


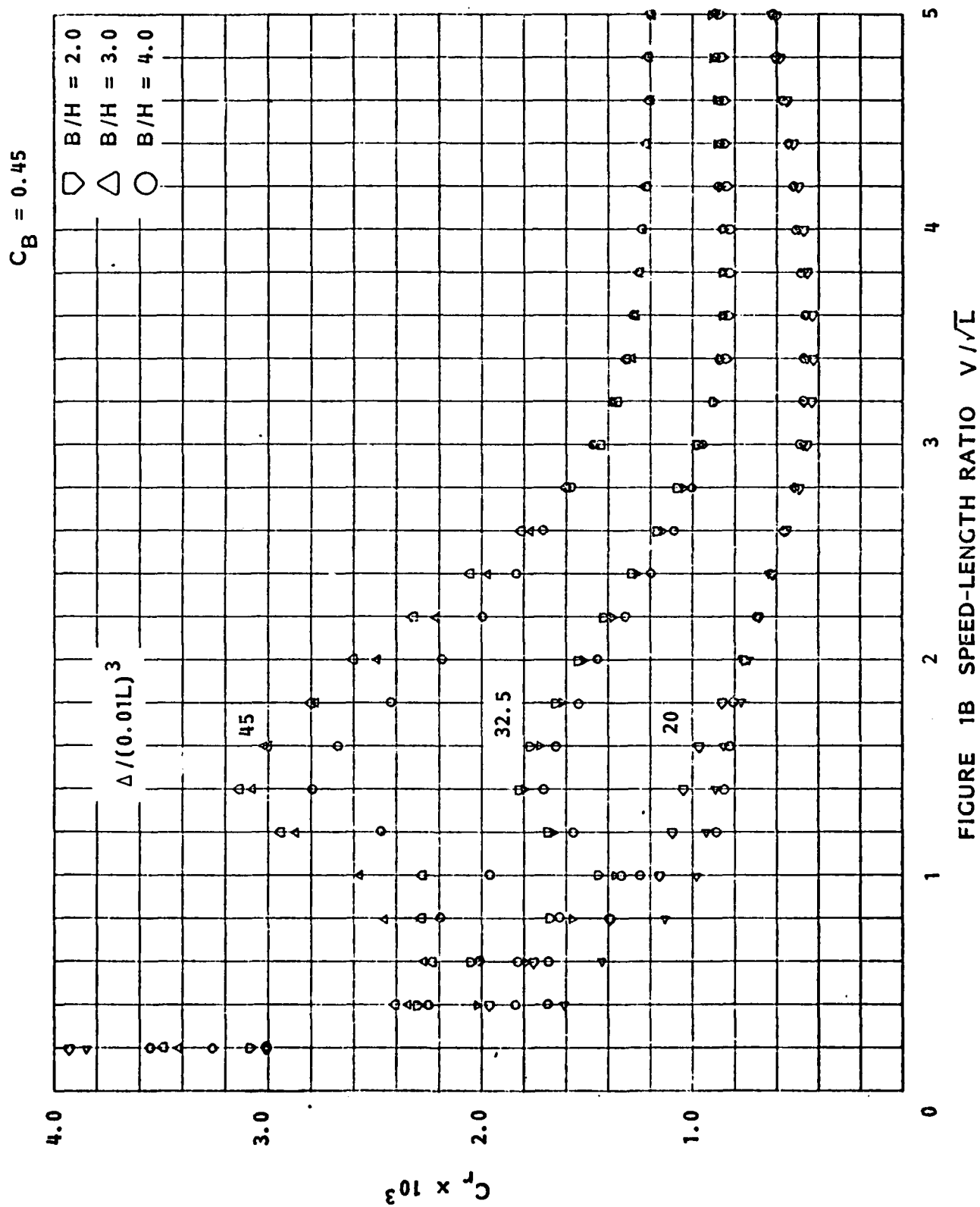
8) A comparison of calculated results with the experimental results of NSRDC Series 64 shows good agreement, especially at the larger values of  $B/H$  (3 and 4) and lends credence to the theory.

9) Extensions are indicated.

REFERENCES

1. Yeh, H. Y. H., "Series 64 Resistance Experiments on High-Speed Displacement Forms," Marine Tech., Vol. 2, No. 3, 1965.
2. Shuford, C. L., Jr., "A Theoretical and Experimental Study of Planing Surfaces Including Effect of Cross Section and Planform," NACA TN 3939, 1957.
3. Hsu, C. C., "On the Motions of High Speed Planing Craft," HYDRONAUTICS, Incorporated Technical Report 603-1, May 1967.
4. Tulin, M. P., "The Theory of Slender Surfaces Planing at High Speed," Schiffstechnik, 4, 1956, 125-133.
5. Ogilvie, T. F., "Non-Linear High-Froude-Number Free-Surface Problems," J. Engineering Math., 1, 1967, 215-235.
6. Van Eseltine, R. T., and Haussing, H. J., "Flow About Transom Sterns," The Third International Conference on Numerical Ship Hydrodynamics, June 1981, Paris, France.

FIGURE 1A RESIDUARY-RESISTANCE COEFFICIENTS,  $C_r = R_r / 1/2 \rho S V^2$



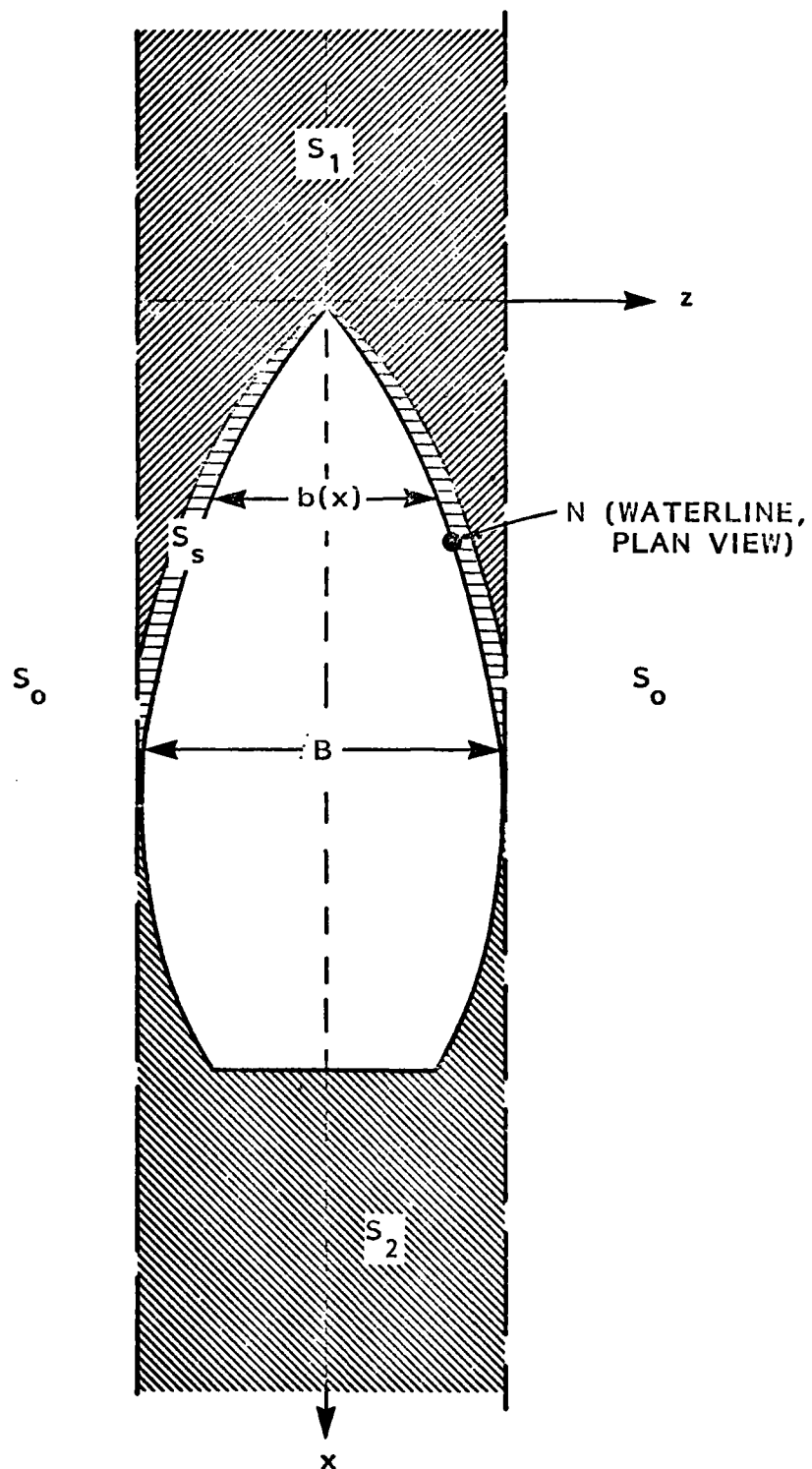


FIGURE 2 - FREE SURFACE REGIONS - HIGH SPEED SHIP

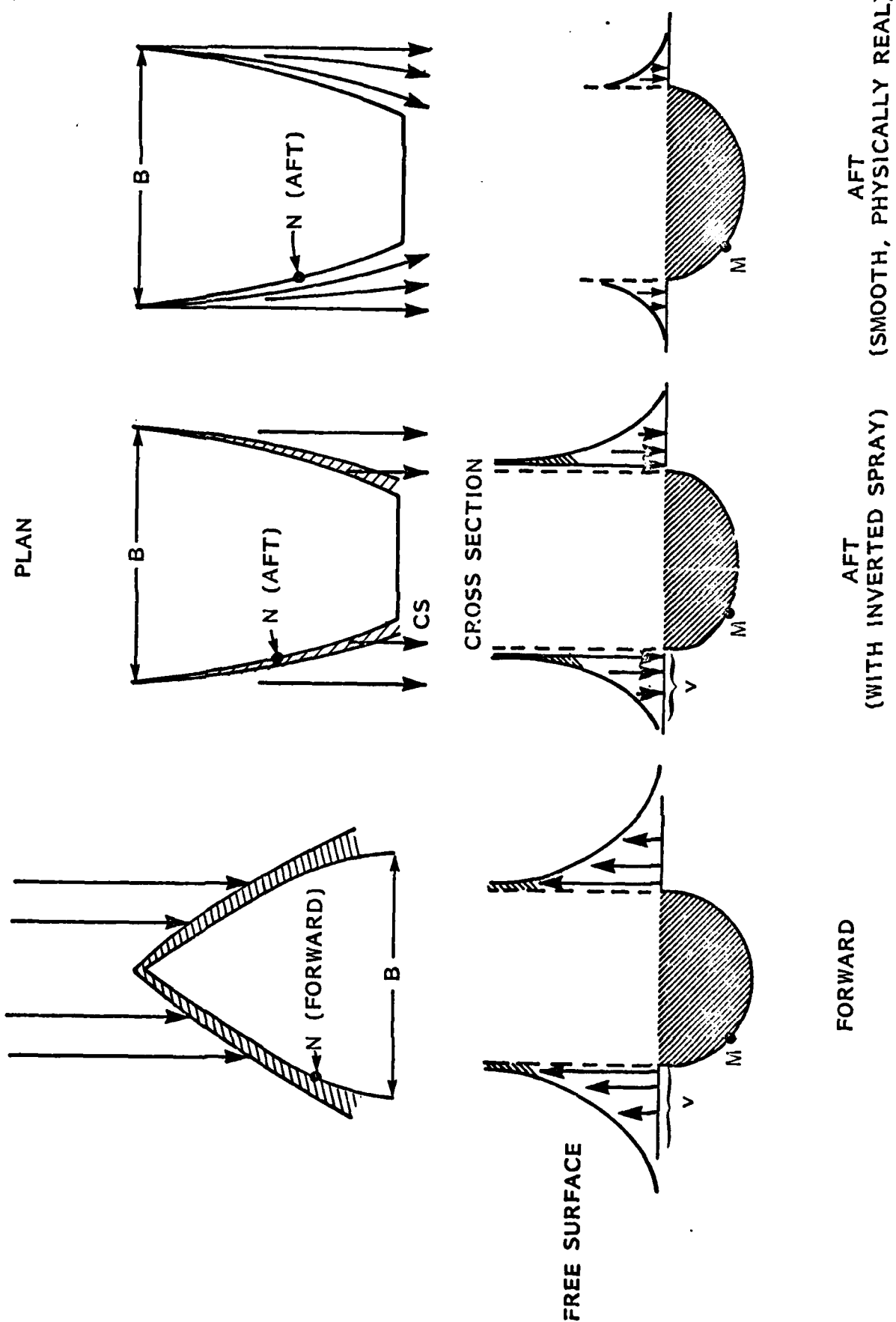


FIGURE 3 - SCHEMATIC OF STREAMLINES AND FREE SURFACE SHAPE

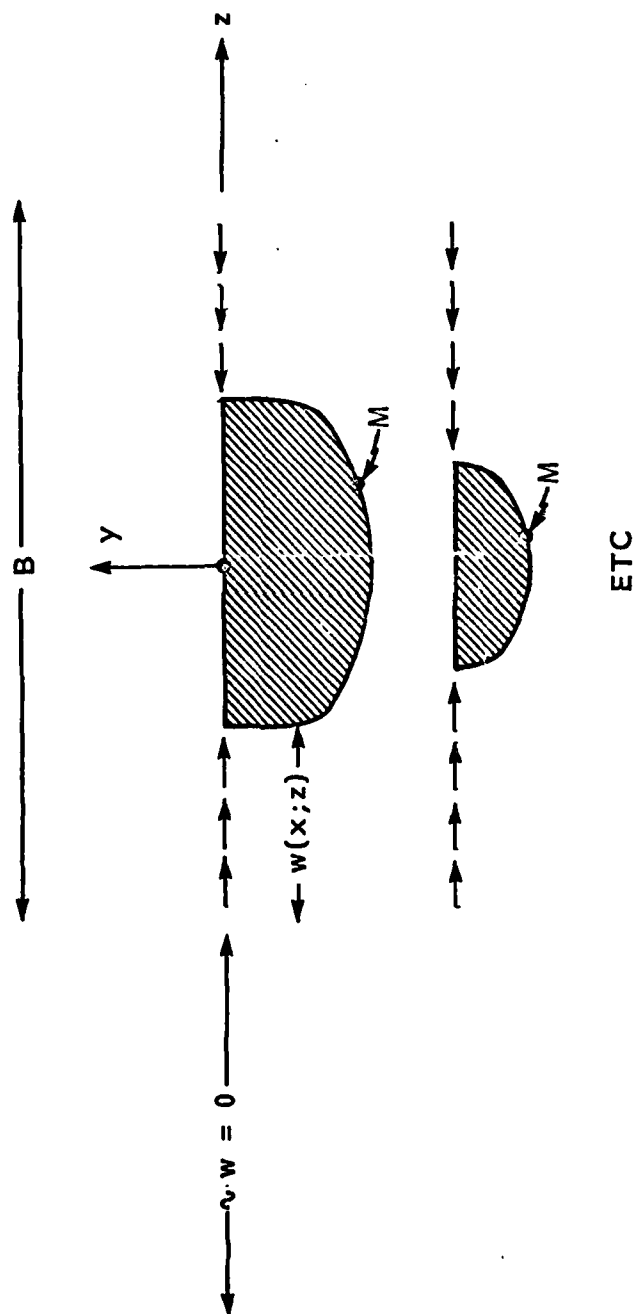
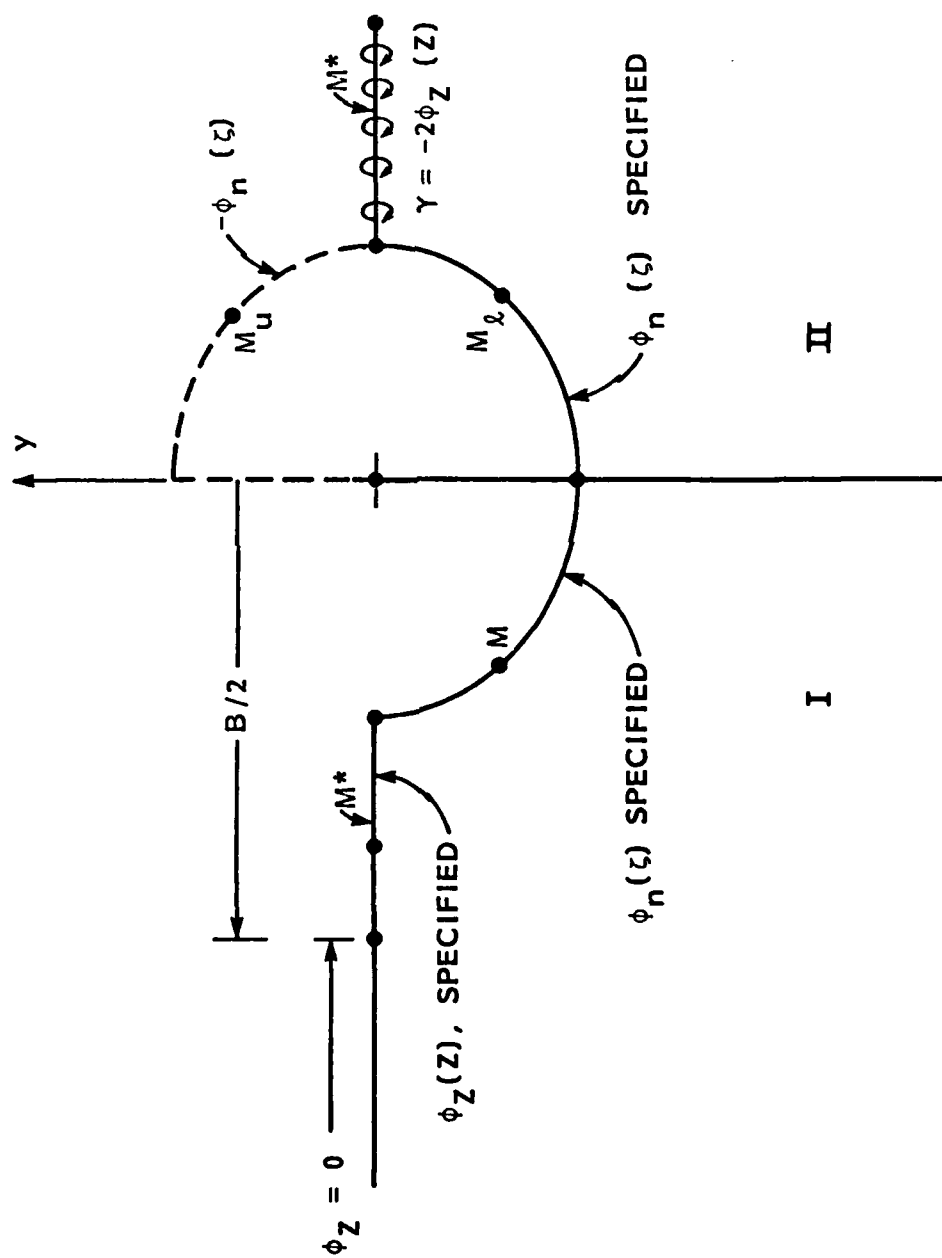


FIGURE 4 - TYPICAL AFT CROSS-SECTIONS SHOWING TRANSVERSE VELOCITIES ( $y \approx 0$ ) IN REAR SHADOW OF HULL



## THE BOUNDARY VALUE PROBLEMS I & II ARE EQUIVALENT

**FIGURE 5 - THE PROBLEM IN THE CROSS-SECTION  
(GIVEN X, AFT)**



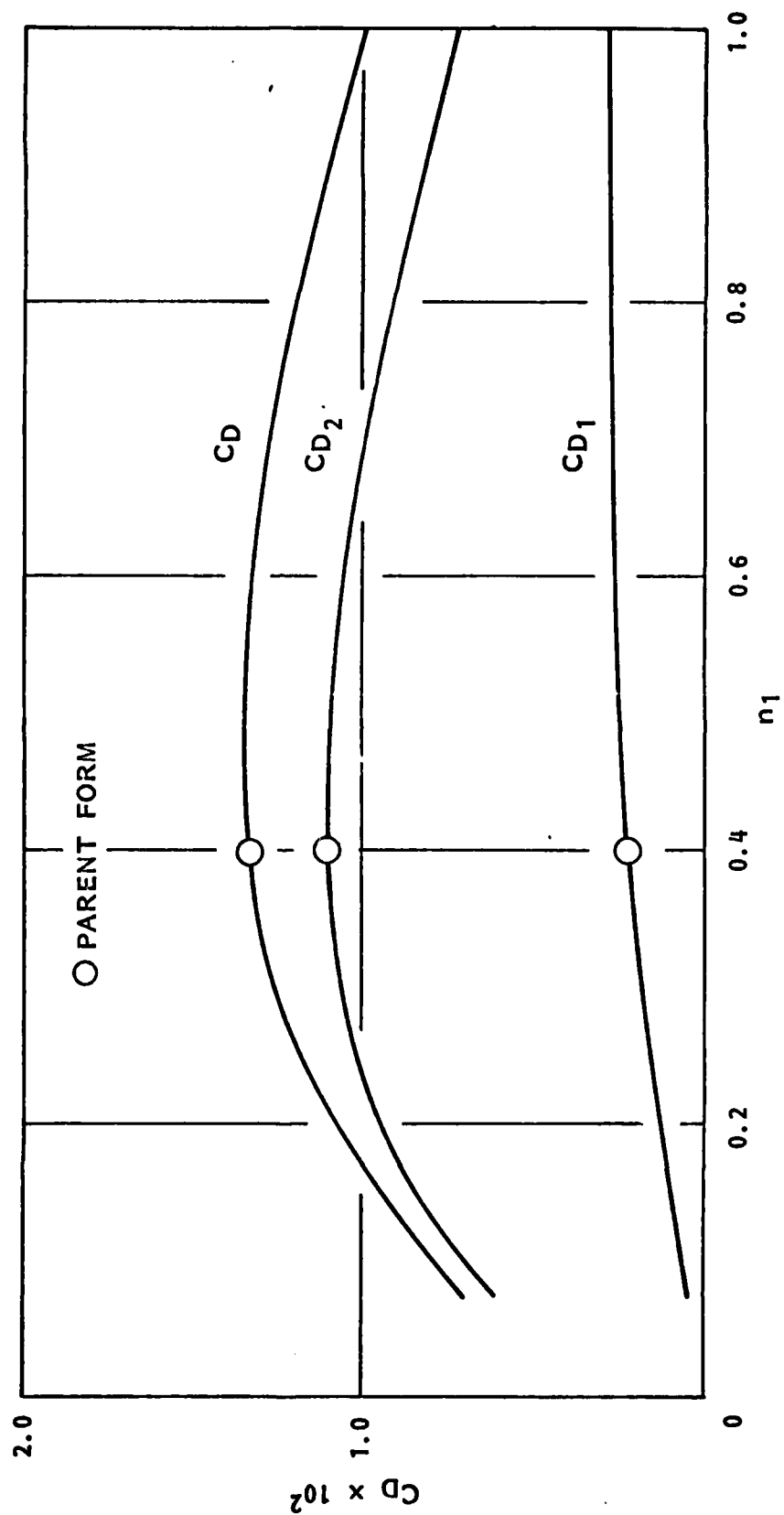


FIGURE 6  $C_D$  Vs  $n_1$

-27-

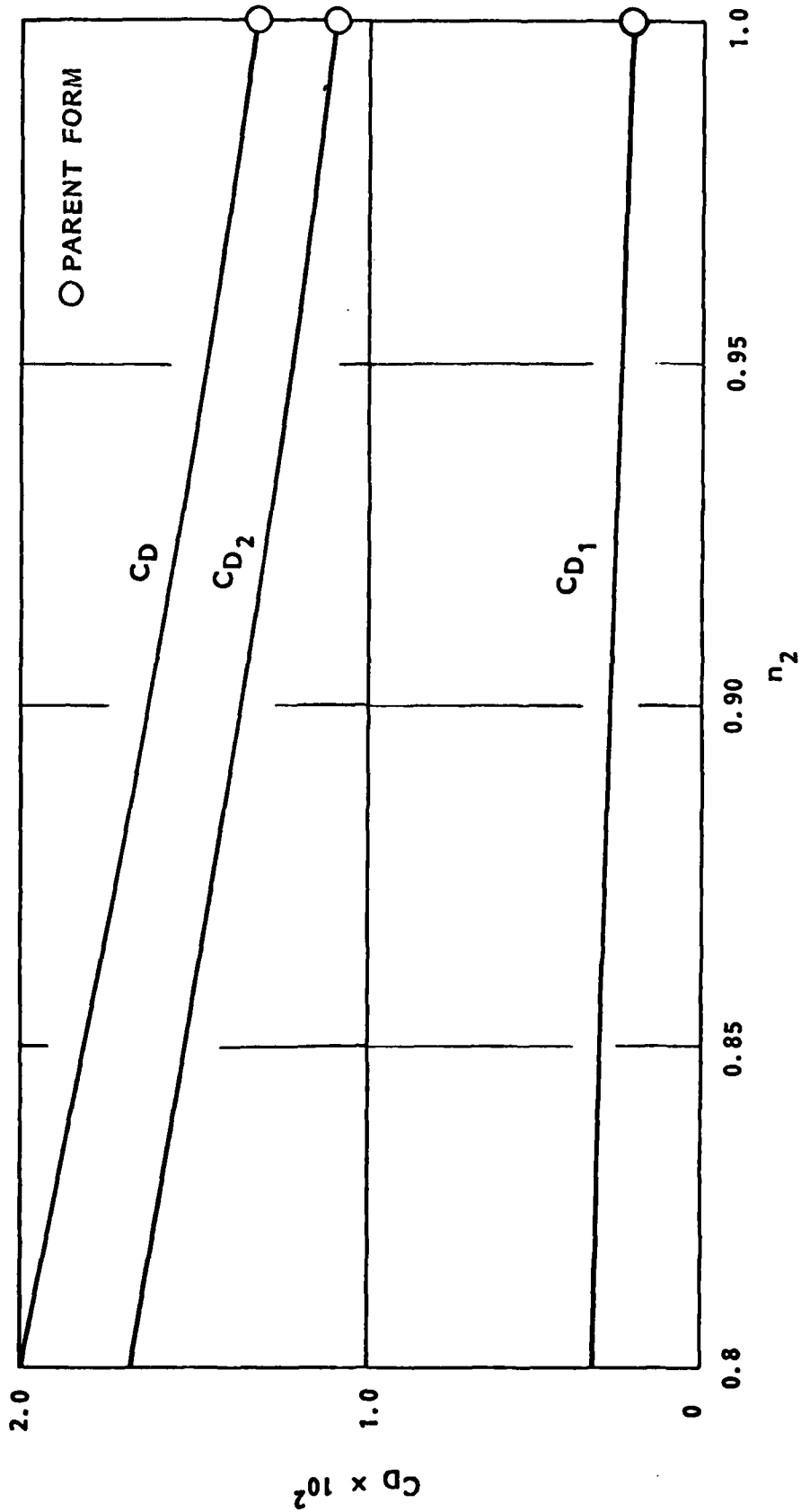
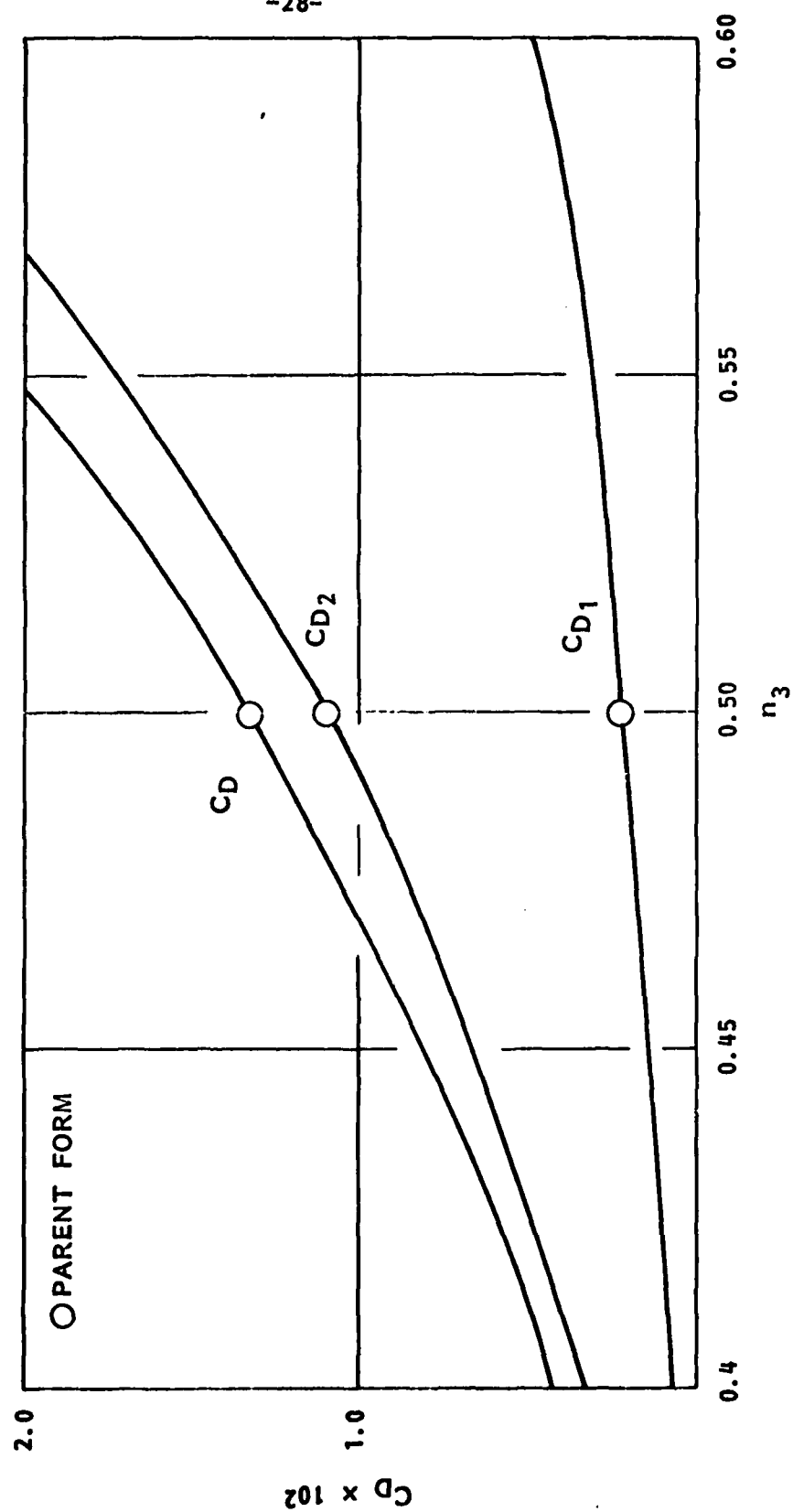


FIGURE 7  $C_D$  Vs  $n_2$

FIGURE 8  $C_D$  Vs  $n_3$

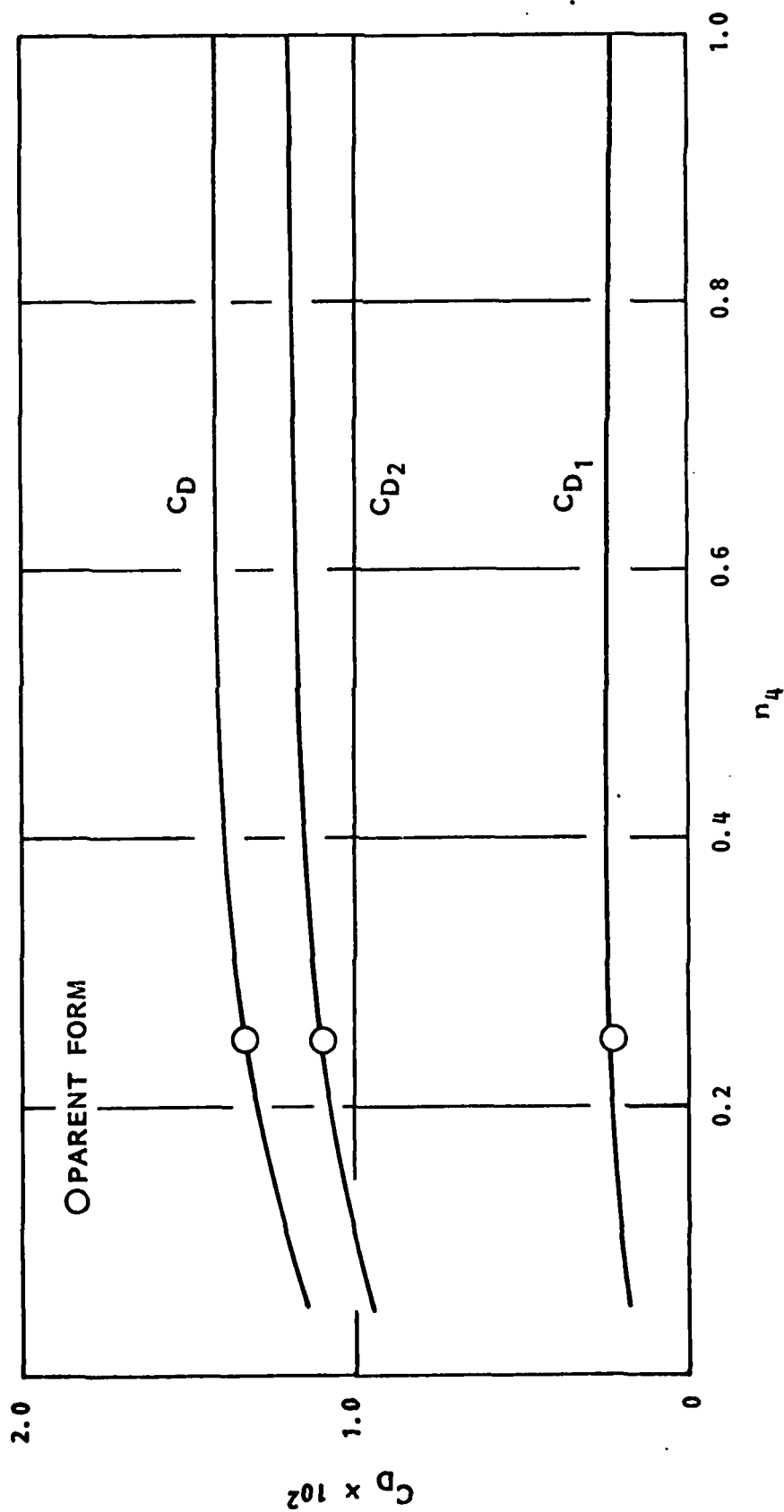


FIGURE 9  $C_D$  Vs  $n_4$

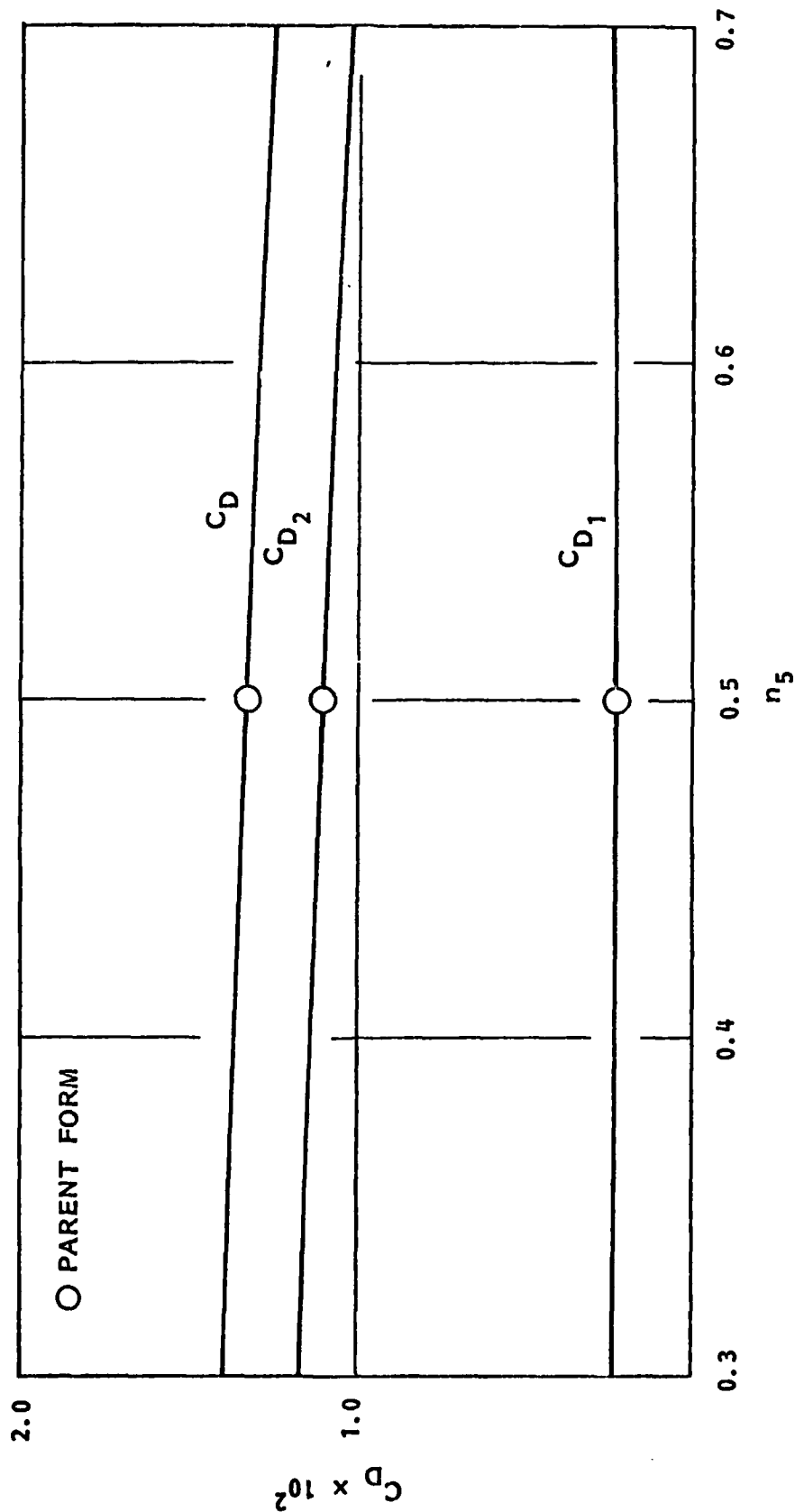
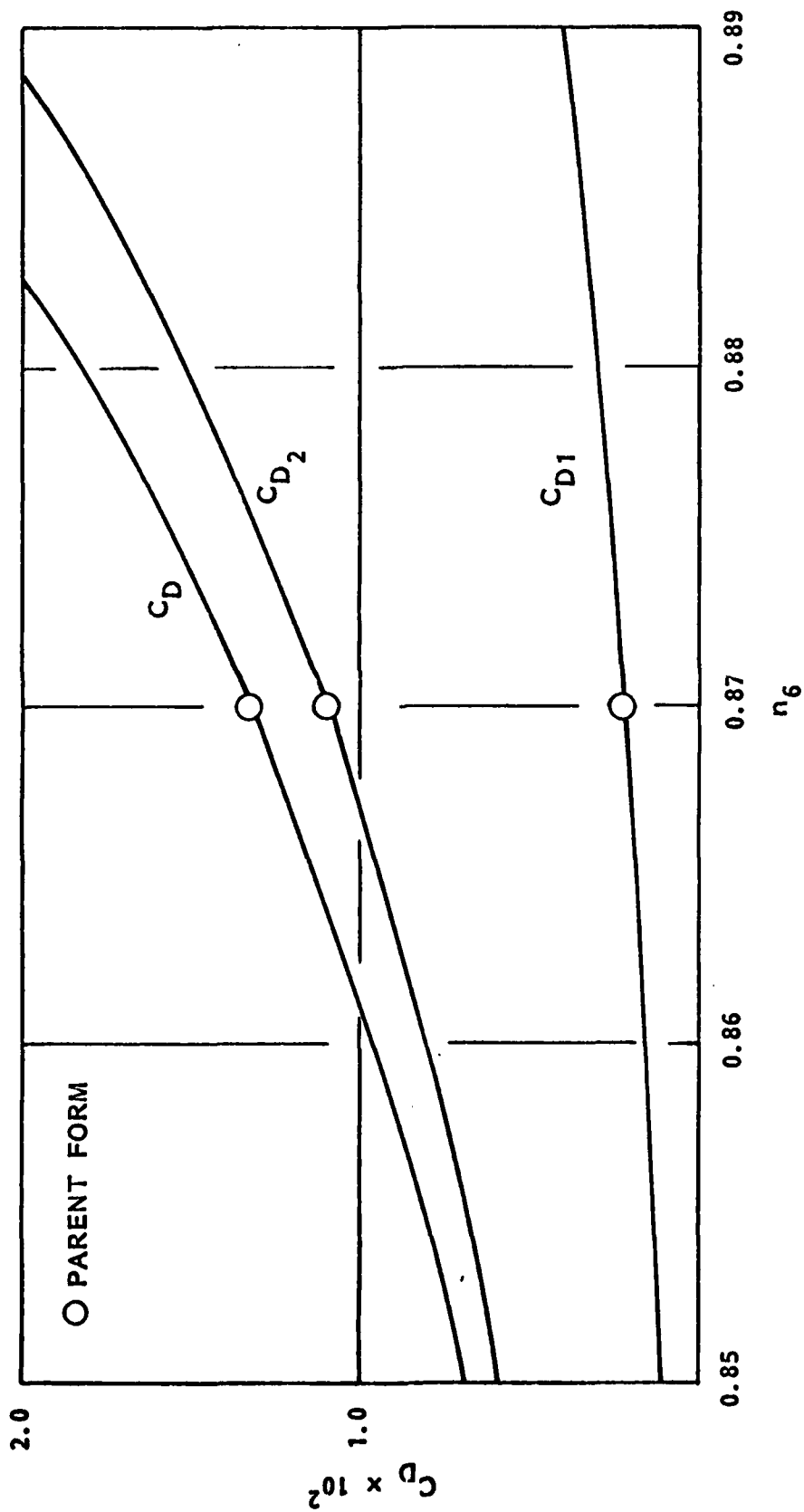


FIGURE 10  $C_D$  Vs  $n_5$

FIGURE 11  $C_D$  Vs  $\eta_6$

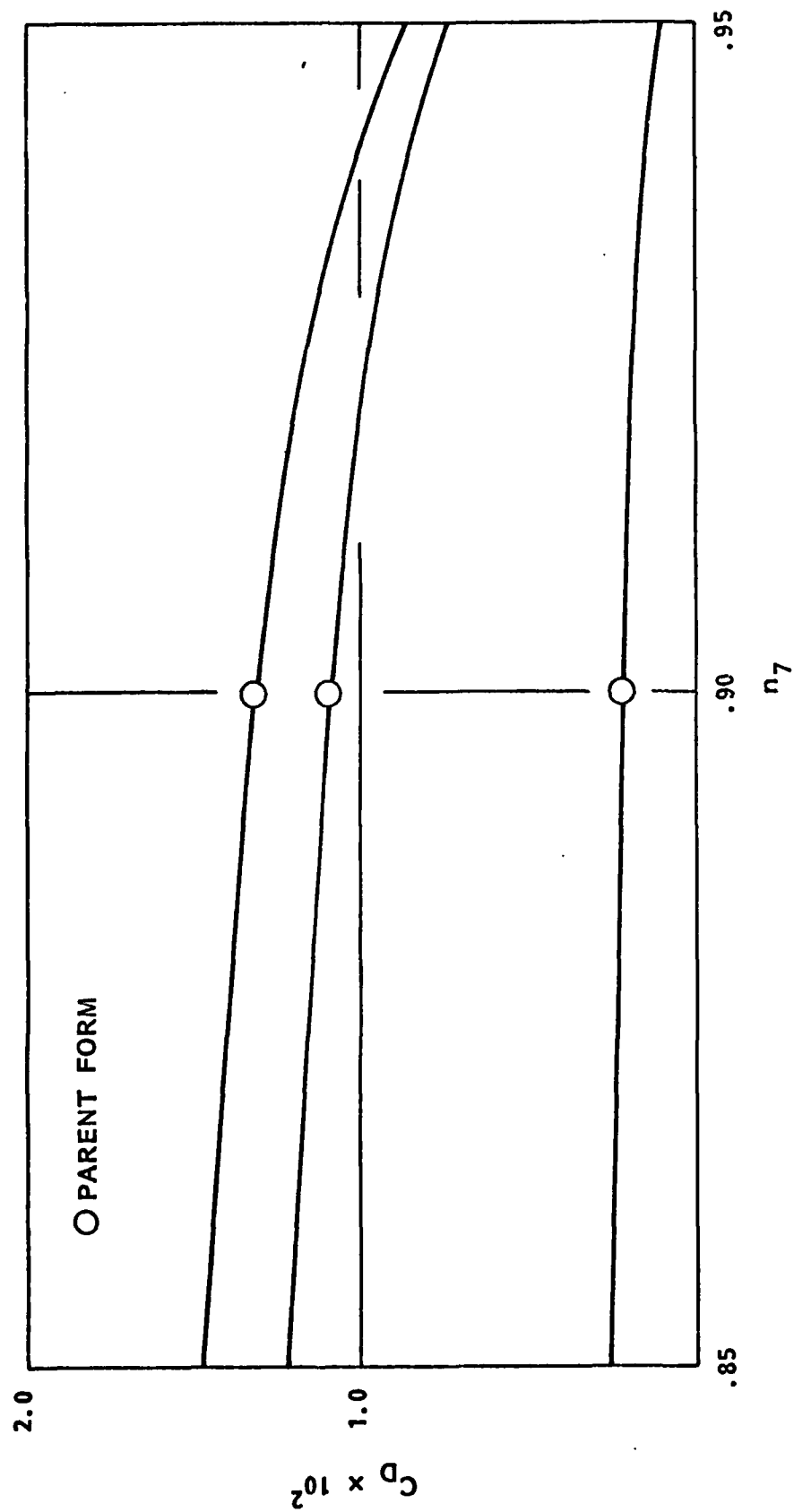


FIGURE 12  $C_D$  Vs  $n_7$

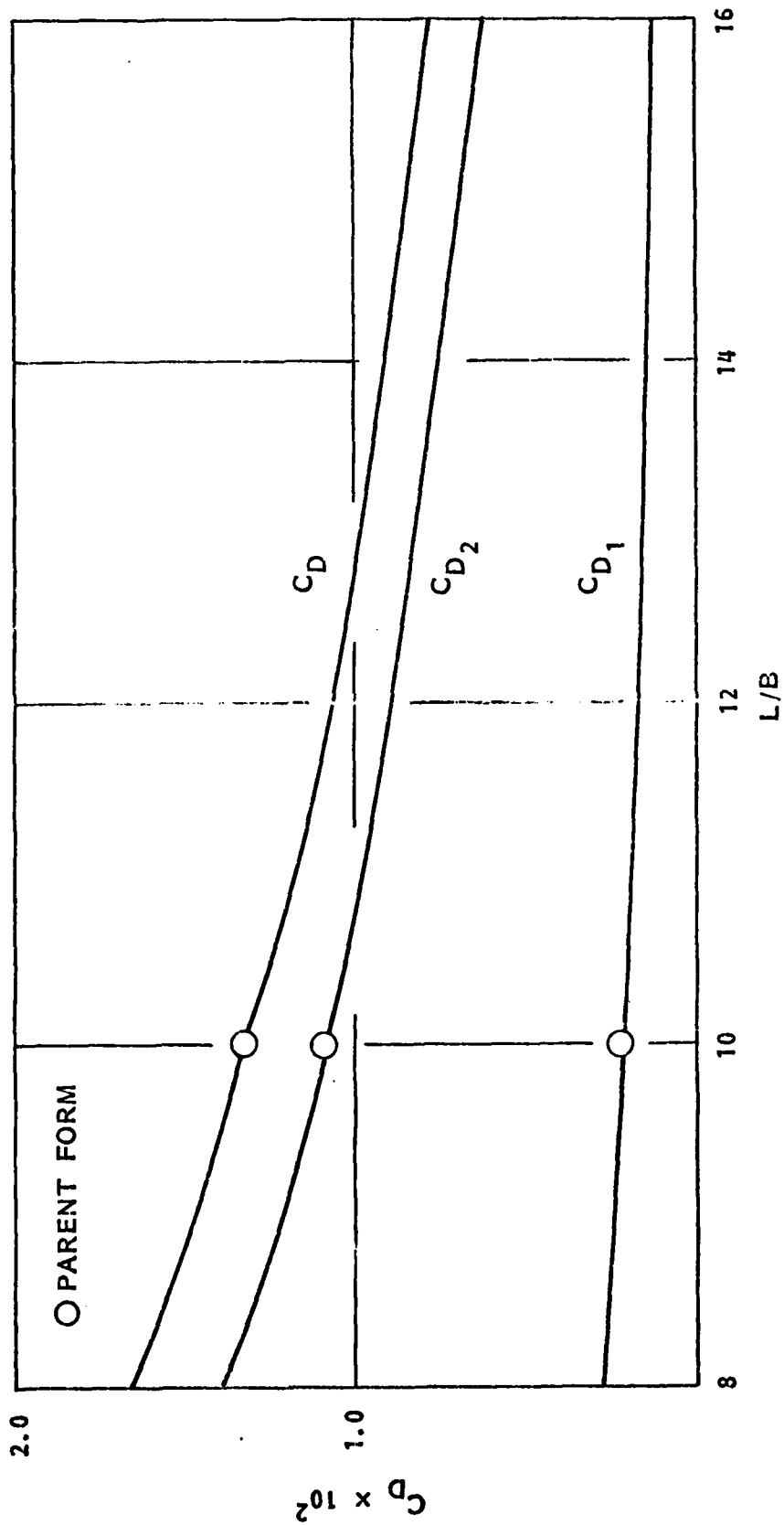


FIGURE 13  $C_D$  Vs  $L/B$



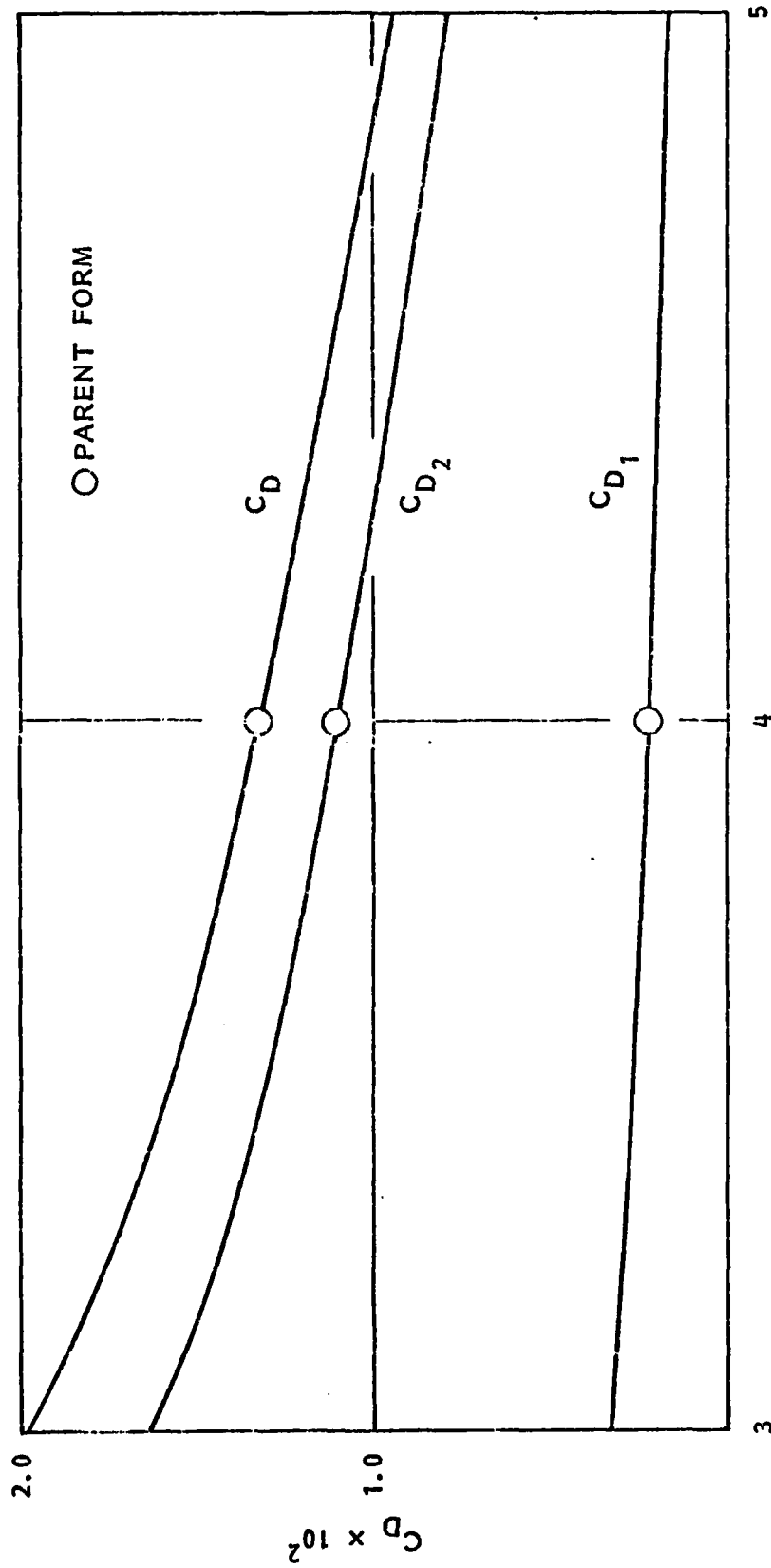


FIGURE 14  $C_D$  Vs  $B/H$

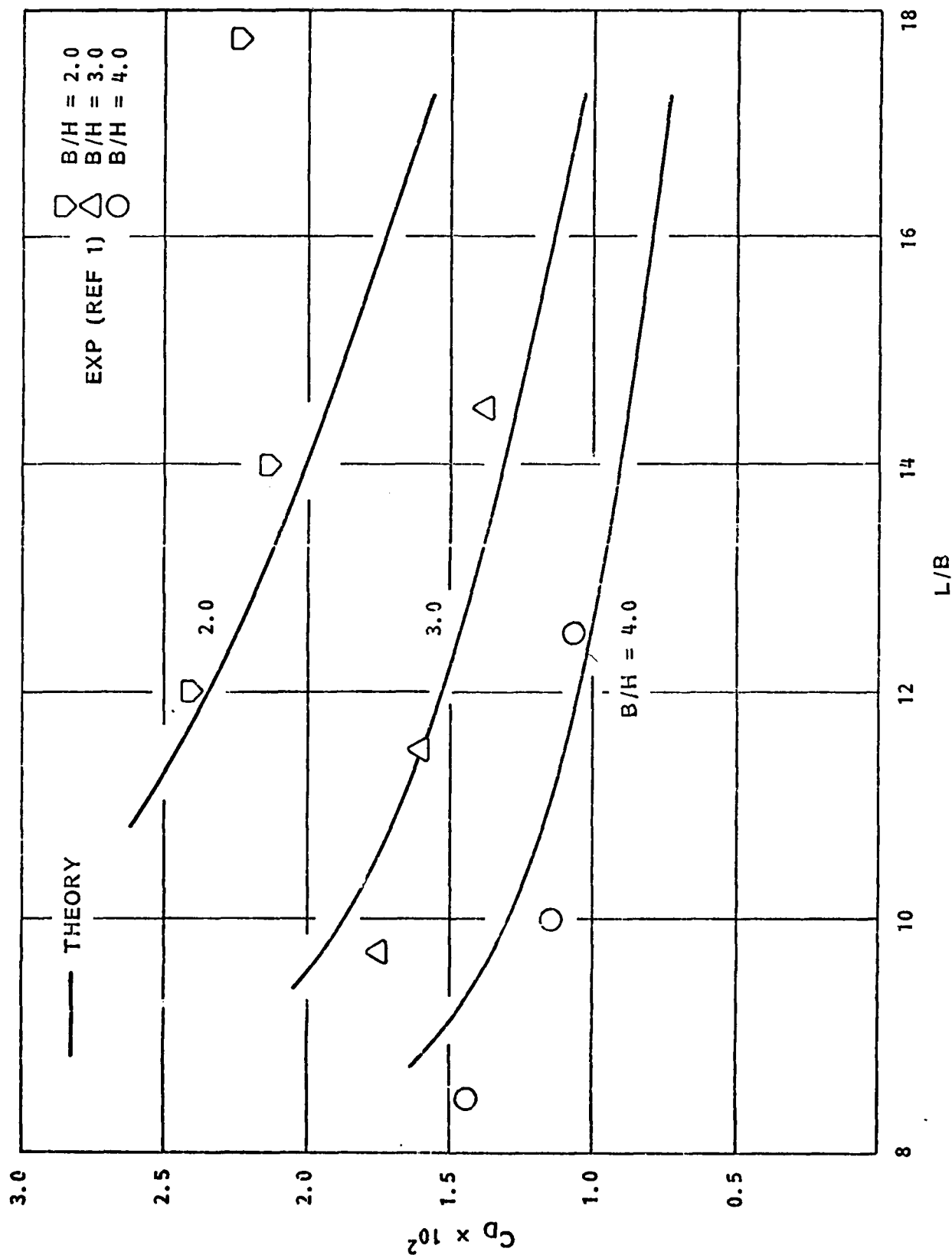


FIGURE 15a COMPARISONS WITH EXPERIMENTS, BLOCK COEFFICIENT = 0.55

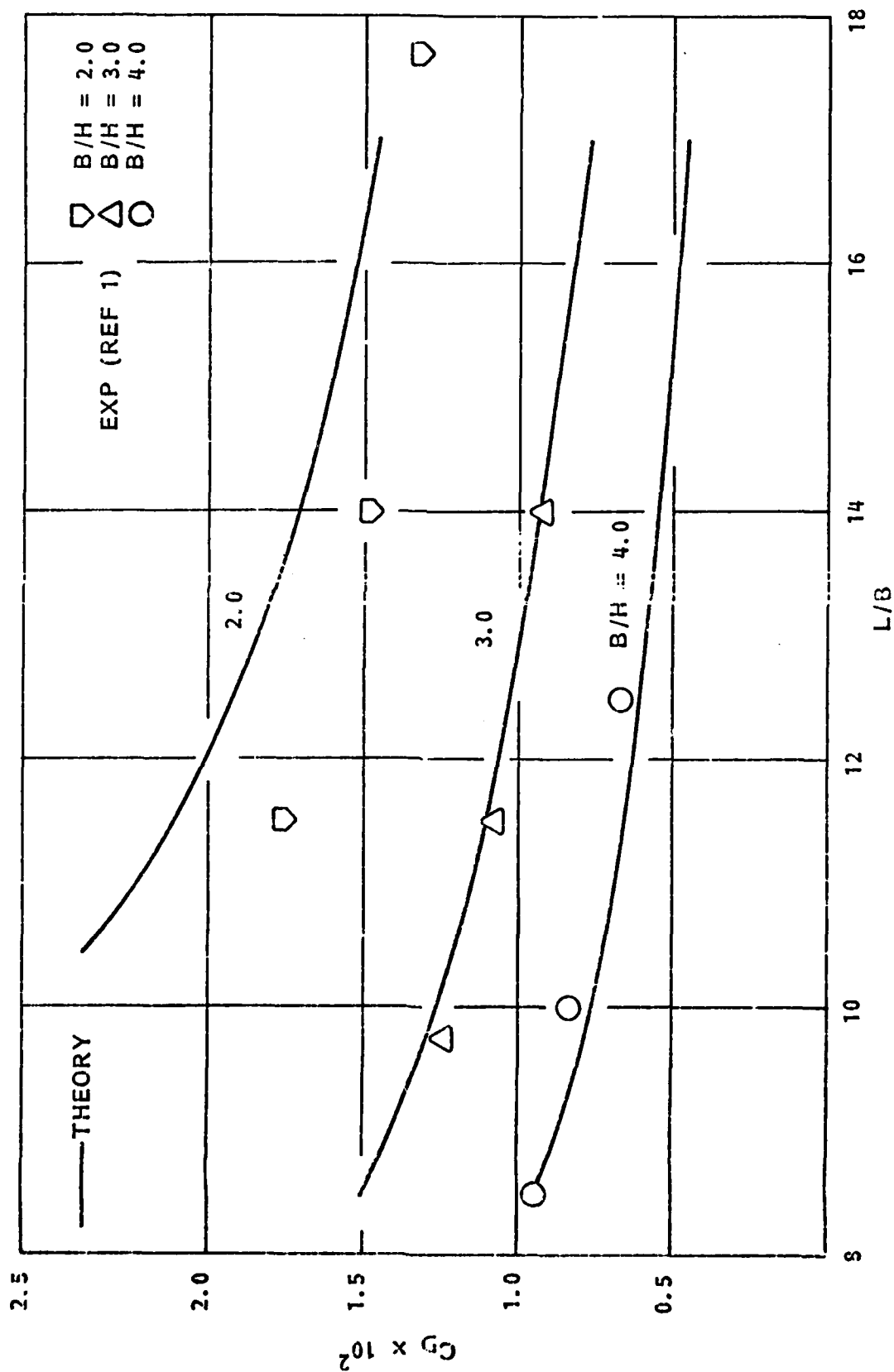


FIGURE 15b CONTINUED, BLOCK COEFFICIENT = 0.15

DISTRIBUTION LIST FOR UNCLASSIFIED  
TECHNICAL REPORTS AND REPRINTS ISSUED UNDER  
CONTRACT N00014-78-C-0014 TASK 062-596

All addressees receive one copy unless otherwise specified.

Defense Technical Information Center  
Cameron Station  
Alexandria, VA 22314 12 copies

Professor Bruce Johnson  
U.S. Naval Academy  
Engineering Department  
Annapolis, MD 21402

Library  
U.S. Naval Academy  
Annapolis, MD 21402

Technical Library  
David W. Taylor Naval Ship Research  
and Development Center  
Annapolis Laboratory  
Annapolis, MD 21402

Professor C. -S. Yih  
The University of Michigan  
Department of Engineering Mechanics  
Ann Arbor, MI 48109

Professor T. Francis Ogilvie  
Massachusetts Institute of Technology  
Department of Ocean Engineering  
Cambridge, MA 02139

Office of Naval Research  
Code 211  
800 N. Quincy Street  
Arlington, VA 22217

Office of Naval Research  
Code 438  
800 N. Quincy Street  
Arlington, VA 22217 3 copies

Office of Naval Research  
Code 473  
800 N. Quincy Street  
Arlington, VA 22217

NASA Scientific and Technical  
Information Facility  
P. O. Box 8757  
Baltimore/Washington International  
Airport  
Maryland 21240

Professor Paul M. Naghdi  
University of California  
Department of Mechanical Engineering  
Berkeley, CA 94720

Librarian  
University of California  
Department of Naval Architecture  
Berkeley, CA 94720

Professor John V. Wehausen  
University of California  
Department of Naval Architecture  
Berkeley, CA 94720

Library  
David W. Taylor Naval Ship Research  
and Development Center  
Code 522.1  
Bethesda, MD 20084

Mr. Justin H. McCarthy, Jr.  
David W. Taylor Naval Ship Research  
and Development Center  
Code 1540  
Bethesda, MD 20084

Dr. William B. Morgan  
David W. Taylor Naval Ship Research  
and Development Center  
Code 1500  
Bethesda, MD 20084

Director  
Office of Naval Research Eastern/Central  
Regional Office  
Building 114, Section D  
606 Summer Street  
Boston, MA 02210

Library  
Naval Weapons Center  
China Lake, CA 93555

Technical Library  
Naval Surface Weapons Center  
Dahlgren Laboratory  
Dahlgren, VA 22418

Technical Documents Center  
Army Mobility Equipment Research Center  
Building 315  
Fort Belvoir, VA 22060

Technical Library  
Webb Institute of Naval Architecture  
Glen Cove, NY 11542

Dr. J. P. Breslin  
Stevens Institute of Technology  
Davidson Laboratory  
Castle Point Station  
Hoboken, NJ 07030

Professor Louis Landweber  
The University of Iowa  
Institute of Hydraulic Research  
Iowa City, IA 52242

R. E. Gibson Library  
The Johns Hopkins University  
Applied Physics Laboratory  
Johns Hopkins Road  
Laurel, MD 20810

Lorenz G. Straub Library  
University of Minnesota  
St. Anthony Falls Hydraulic Laboratory  
Minneapolis, MN 55414

Library  
Naval Postgraduate School  
Monterey, CA 93940

Technical Library  
Naval Underwater Systems Center  
Newport, RI 02840

Engineering Societies Library  
345 East 47th Street  
New York, NY 10017

The Society of Naval Architects and  
Marine Engineers  
One World Trade Center, Suite 1369  
New York, NY 10048

Technical Library  
Naval Coastal System Laboratory  
Panama City, FL 32401

Professor Theodore Y. Wu  
California Institute of Technology  
Engineering Science Department  
Pasadena, CA 91125

Director  
Office of Naval Research Western Regional  
Office  
1030 E. Green Street  
Pasadena, CA 91101

Technical Library  
Naval Ship Engineering Center  
Philadelphia Division  
Philadelphia, PA 19112

Army Research Office  
P. O. Box 12211  
Research Triangle Park, NC 27709

Editor  
Applied Mechanics Review  
Southwest Research Institute  
8500 Culebra Road  
San Antonio, TX 78206

Technical Library  
Naval Ocean Systems Center  
San Diego, CA 92152

ONR Scientific Liaison Group  
American Embassy - Room A-407  
APO San Francisco 96503

Librarian  
Naval Surface Weapons Center  
White Oak Laboratory  
Silver Spring, MD 20910

Defense Research and Development Attache  
Australian Embassy  
1601 Massachusetts Avenue, NW  
Washington, DC 20036

Librarian Station 5-2  
Coast Guard Headquarters  
NASSIF Building  
400 Seventh Street, SW  
Washington, DC 20591

Library of Congress  
Science and Technology Division  
Washington, DC 20540

Dr. A. L. Slafkosky  
Scientific Advisor  
Commandant of the Marine Corps  
Code AX  
Washington, DC 20380

Maritime Administration  
Office of Maritime Technology  
14th & E Streets, NW  
Washington, DC 20230

Maritime Administration  
Division of Naval Architecture  
14th & E Streets, NW  
Washington, DC 20230

Dr. G. Kulin  
National Bureau of Standards  
Mechanics Section  
Washington, DC 20234

Naval Research Laboratory  
Code 2627  
Washington, DC 20375     6 copies

Library  
Naval Sea Systems Command  
Code 09GS  
Washington, DC 20362

Mr. Thomas E. Peirce  
Naval Sea Systems Command  
Code 03512  
Washington, DC 20362

Oceanographer of the Navy  
200 Stovall Street  
Alexandria, VA 22332

Office of Naval Research  
Code 481  
800 N. Quincy Street  
Arlington, VA 22217

Professor Richard W. Miksad  
The University of Texas at Austin  
Department of Civil Engineering  
Austin, TX 78712

Dr. Robert R. Long  
The Johns Hopkins University  
Department of Earth and  
Planetary Sciences  
Baltimore, MD 21218

Professor Owen M. Phillips  
The Johns Hopkins University  
Department of Earth and  
Planetary Sciences  
Baltimore, MD 21218

Professor C. C. Mei  
Massachusetts Institute of Technology  
Department of Civil Engineering  
Cambridge, MA 02139

Professor David J. Benney  
Massachusetts Institute of Technology  
Department of Mathematics  
Cambridge, MA 02139

Professor E. Mollo-Christensen  
Massachusetts Institute of Technology  
Department of Meteorology  
Room 54-1722  
Cambridge, MA 02139

Professor Justin E. Kerwin  
Massachusetts Institute of Technology  
Department of Ocean Engineering  
Cambridge, MA 02139

Professor John W. Miles  
University of California, San Diego  
Institute of Geophysics and  
Planetary Physics, A-025  
La Jolla, CA 92093

Dr. E. W. Montroll  
Physical Dynamics, Inc.  
P. O. Box 556  
La Jolla, CA 92038

Director  
Scripps Institute of Oceanography  
University of California  
La Jolla, CA 92037

Dr. Steven A. Orszag  
Cambridge Hydrodynamics, Inc.  
54 Baskin Road  
Lexington, MA 02173

Dr. Steven C. Crow  
President, Poseidon Research  
11777 San Vicente Blvd., Suite 641  
Los Angeles, CA 90049

Professor Frederick K. Browand  
University of Southern California  
University Park  
Department of Aerospace Engineering  
Los Angeles, CA 90007

Professor John Laufer  
University of Southern California  
University Park  
Department of Aerospace Engineering  
Los Angeles, CA 90007

Professor T. N. Stevenson  
University of Manchester  
Department of the Mechanics of Fluids  
Manchester M13 9PL, England

Professor Jin Wu  
University of Delaware  
College of Marine Studies  
Newark, DE 19711

Professor R. C. MacCamy  
Carnegie Institute of Technology  
Department of Mathematics  
Pittsburgh, PA 15213

Professor Norman J. Zabusky  
University of Pittsburgh  
Department of Mathematics and Statistics  
Pittsburgh, PA 15260

Dr. Harvey Segur  
Aeronautical Research Associates  
of Princeton, Inc.  
50 Washington Road  
Princeton, NJ 08540

Professor J. T. C. Liu  
Brown University  
Division of Engineering  
Providence, RI 02912

Professor C. H. Su  
Brown University  
Division of Applied Mathematics  
Providence, RI 02912

Dr. Jack W. Hoyt  
Naval Ocean Systems Center  
Code 2501  
San Diego, CA 92152

Professor Milton Van Dyke  
Stanford University  
Department of Aeronautics  
and Astronautics  
Stanford, CA 94305

Professor J. F. Thompson  
Mississippi State University  
Department of Aerophysics and  
Aerospace Engineering  
State College, MS 39762

Professor Richard L. Pfeffer  
Florida State University  
Geophysical Fluid Dynamics Institute  
Tallahassee, FL 32306

Professor Ruby E. Krishnamurti  
Florida State University  
Department of Oceanography  
Tallahassee, FL 32306

Professor Timothy W. Kao  
The Catholic University of America  
Department of Civil Engineering  
Washington, DC 20064

Professor Phillip Mandel  
Massachusetts Institute of Technology  
Department of Ocean Engineering  
Cambridge, MA 02139

Professor J. Nicholas Newman  
Massachusetts Institute of Technology  
Department of Ocean Engineering  
Room 5-324A  
Cambridge, MA 02139

Professor Ronald W. Yeung  
Massachusetts Institute of Technology  
Department of Ocean Engineering  
Cambridge, MA 02139

Professor S. I. Pai  
University of Maryland  
Institute of Fluid Dynamics  
and Applied Mathematics  
College Park, MD 20742

Computation and Analyses Laboratory  
Naval Surface Weapons Center  
Dahlgren Laboratory  
Dahlgren, VA 22418

Dr. Robert K. -C. Chan  
JAYCOR  
1401 Camino Del Mar  
Del Mar, CA 92014

Professor K. E. Shuler  
University of California, San Diego  
Department of Chemistry  
La Jolla, CA 92093

Professor Hsien-Ping Pao  
The Catholic University of America  
Department of Civil Engineering  
Washington, DC 20064

Commander  
Naval Oceanographic Office  
Washington, DC 20373

Dr. J. O. Elliot  
Naval Research Laboratory  
Code 8310  
Washington, DC 20375

Naval Research Laboratory  
Code 8340  
Washington, DC 20375

Naval Ship Engineering Center  
Code 6110  
Washington, DC 20362

Naval Ship Engineering Center  
Code 6114  
Washington, DC 20362

Naval Ship Engineering Center  
Code 6136  
Washington, DC 20362

Dr. Gary S. Deem  
Bell Telephone Laboratories, Inc.  
1 Whippany Road  
Whippany, NJ 07981

Mr. D. Farmer  
Naval Ocean Research and  
Development Activity  
Code 332  
NSTL Station, MS 39522